A Science Flight Planning Tool

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Chapter 1

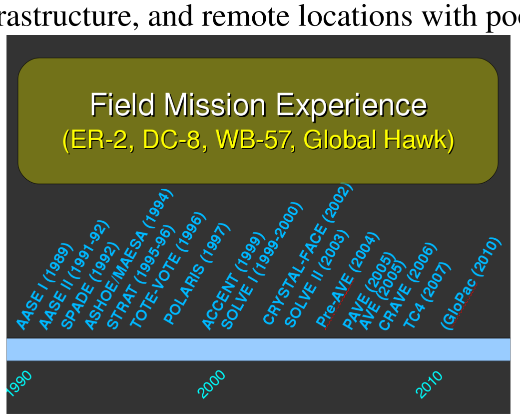
Summary

Aircraft field experiments benefit from a software tool that assists project scientists in working out possible flight scenarios to be submitted to flight operations. Such a tool develops a better understanding among the scientists of a given aircraft's capabilities, and it encourages clearer and more thorough communications between the scientists and flight ops personnel. To be most useful, a science flight planning tool should provide a variety of user-selectable and user-configurable scientific displays of atmospheric data enhanced by markers for locations and areas. Moreover, it must be able to simulate a proposed flight with a reasonable degree of accuracy in its timings and altitude profiles. A simple program for drawing way points on a map will not suffice. The new GSFC flight planner is a successful example that incorporates most of the features desired in such a tool.

Chapter 2

What do we know?

Drs. Paul Newman and Leslie Lait work in the Atmospheric Chemistry and Dynamics Branch at NASA's Goddard Space Flight Center. They have participated in numerous aircraft field experiments: AASE I (1989), AASE II (1991–1992), SPADE (1992), ASHOE-MAESA (1994), STRAT (1995–1996), TOTE-VOTE (1996), POLARIS (1997), ACCENT (1999), SOLVE I (1999–2000) CRYSTAL-FACE (2002), SOLVE II (2003), pre-AVE (2004), PAVE (2005), AVE (2005), CRAVE (2006), TC4 (2007), and GloPac (2010). We are now preparing for the ATTREX and HS3 missions. These field experiments had a variety of scientific goals. The aircraft platforms have included the ER-2, DC-8, WB-57, and Global Hawk. These platforms have carried payloads of both in situ and remote sensing instruments. We have operated from NASA facilities with good communications infrastructure, and remote locations with poorer connectivity.



In 1991, we began developing flight planning software that has let us plan flights for each of those subsequent missions. The software started out simple, having few capabilities. But over the past 20 years, as we have encountered new situations and new demands, we have revised and extended the software to meet the needs of the missions. This includes two complete rewrites.

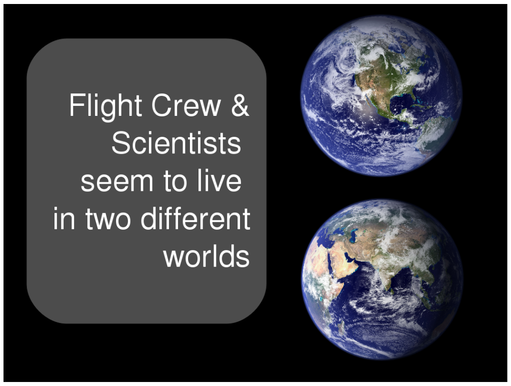
Thus, we have decades of experience with different kinds of aircraft, different kinds of flights, different demands of payloads. We have learned a lot about what is needed in planning science flights. We know what capabilities a flight planning tool has to have if it to be truly useful.

Chapter 3

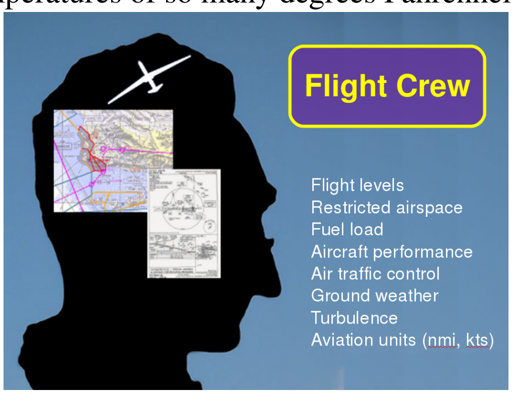
Why a flight planner?

3.1 Purposes

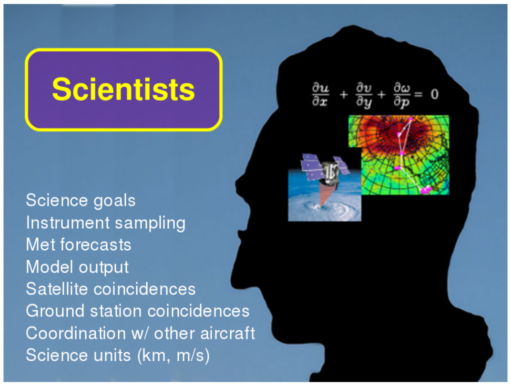
A science flight planner has three basic purposes: to facilitate communications between the mission scintists and the flight operations personnel; to make it easy for mission scientists to work out trial scenarios; and to provide a unifying bridge between long-range planning, short-range-planning, and real-time in-flight monitoring.



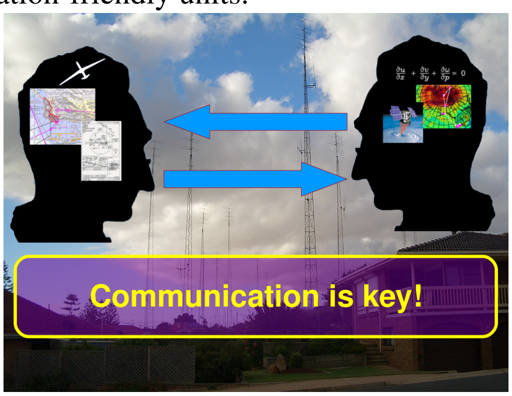
Consider the first purpose, communication. Pilots and the other flight operations folks live in a different world from scientists, and so opportunities for miscommunication abound. Pilots deal with FAA regulations, flight clearances, ground weather, and aircraft performance issues. They fly their aircraft so many nautical miles at certain flight levels, encountering winds of so many knots and temperatures of so many degrees Fahrenheit.



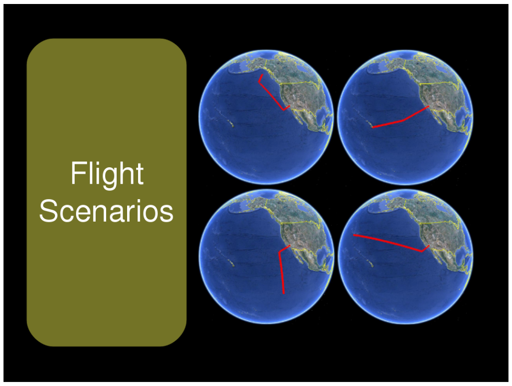
Scientists are focussed on what the atmosphere is doing and how to sample it to fulfill the mission's science goals. They deal with satellite overpasses, ground site measurements, and balancing the conflicting demands of different instruments. For them, the interesting bit of air that they want to sample is so many kilometers away, at a certain potential temperature level, where the winds are so many meters per second and the temperature is of so many Kelvin.



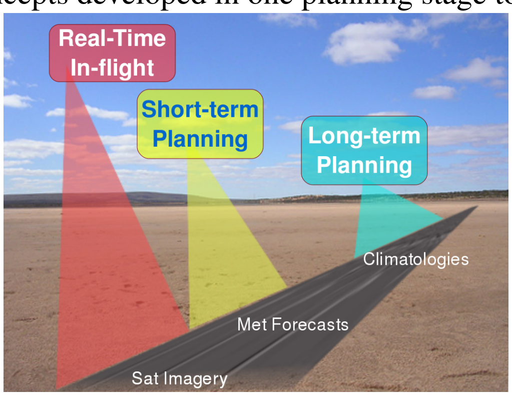
A good flight planning tool will provide a bridge between these two cultures. It should display the meteorological phenomena that the mission scientist is most interested in, but it should also keep him or her aware of the operational constraints. At the touch of a button, the scientist should be able to prepare briefing materials for flight ops, with all of the science-friendly units automatically converted to aviation-friendly units.



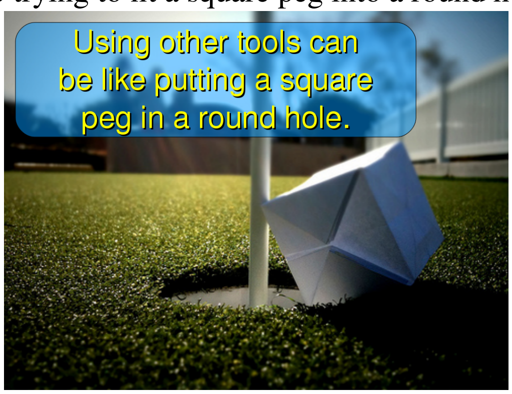
The second purpose of a flight planner is to let the scientists explore a variety of trial scenarios before they present a request to the pilots. Most experiments have multiple instruments and science goals, and these often conflict to some degree. It can be very helpful for the project scientist to be able to examine multiple options before deciding which instrument or goal to favor over another for a given flight. It benefits everyone to have resolved any long discussions or arguments on non-operational matters among the scientists in the absence of the flight crew. Working out scenarios also gives the project scientist the opportunity to develop a better intuitive feel for what a given aircraft can accomplish; this, too makes communicating with the pilots more efficient.



The third purpose of a flight planner is to provide a single tool to assist in planning over multiple time scales. For some missions, a flight planner can be valuable for putting an aircraft in the current meteorological context during a flight so that it may be directed towards (or way from) fast-moving phenomena in real time. For missions in which real-time direction is paramount, the ability to plan the flight path days in advance, based on model forecast fields, can also be important, to develop baseline flight paths from which real-time deviations can be devised. Working out possible flight strategies, based on climatatological data, is also useful for the early stages of mission development, far in advance of any actual flights. A single tool that can be used for the long-term, short-term, and real-time planning time scales is highly advantageous, permitting the plans and concepts developed in one planning stage to be used in the next.



It should be pointed out the ways in which a science flight planner differs from other related tools. For example, typical situational awareness displays are inadequate, because although they can show meteorological data (expecially satellite imagery during a flight) with a flight track, they passively display the track being flown instead of providing an effective means of editing possible tracks. They also tend to lack the ability to model aircraft performance, which is needed to compare different scenarios. A good lfight planning tool can be used to provide situational awareness, but not the other way around. Likewise, an aviation flight planner would be inappropriate for replacing a science flight planner. In the first place, such a tool resides firmly in the world of flight operations, with little capability to examine the kinds of data and model output that scientists require. And in the second place, using an aviation tool would encourage scientists to over-plan flights in too much detail. Tempting scientists to "play pilot" in this way takes them outside of their expertise and must be avoided. These other tools simply do not fill the role of a science flight planner. Attempting to use them in this way is like trying to fit a square peg into a round hole.



Chapter 4

What a good flight planner should do

4.1 Handle a variety of aircraft

A science flight planner needs to be able to plan flights for the various aircraft that NASA uses in its missions. Some fly as high as 70,000 ft, and others can get as low as 1000 ft. Some are restricted to a narrow range of air speeds, while others can fly at a wider variety of speeds. for some, the maximum flight duration is about five hours, and for others it is more like 30 hours. Payloads vary, too: in some missions, an aircraft might have only remote sensing instruments (which tend to prefer a platform flying straight and level). In other missions, the same aircraft may be carrying only in situ instruments (which tend to want lots of vertical profiling). Some instruments look at the sun to measure atmospheric absorption;

others look down a tube that should never be pointed at the sun.

4.2 Handle a variety of flights

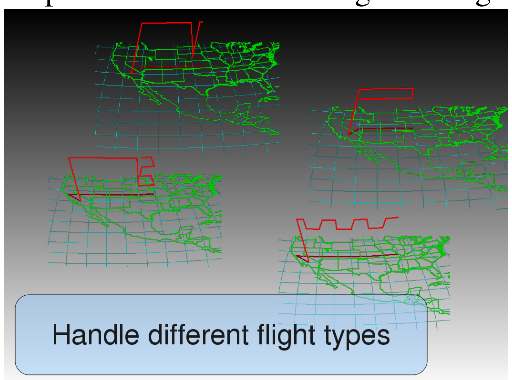
The flight planner must be able to accomodate all sorts of different flight paths. In the horizontal, there can be:

- simple straight lines
- racetrack patterns between two arbitrary points
- paths around rectangular boxes at arbitrary orientations
- circles of arbitrary radii
- "lawnmower" paths, advancing back and forth to cover a box
- radial, or star-shaped patterns to sample hurricanes

In the vertical, you can have:

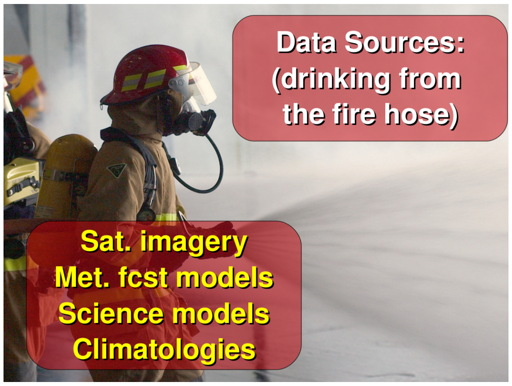
- straight-and-level legs
- cruise climbs
- stepped flights (a series of increasing or decreasing altitudes)
- stacked slights (back and forth at a series of discrete altitudes)
- crenelation flights (up, then level, then down, then level, then up. . .)

Because air speed and fuel consumption vary greatly with altitude for most aircraft, these vertical maneuvers will require the flight planner to model the aircraft's performance in order to get the flight timings right.



4.3 Handle a variety of data types

The data that scientists need can come from all kinds of different sources: Satellite imagery from the U.S. GOES satellites, as well as the geostationary satellite of other nations, will be useful for monitoring in flight. More important for planning flights in advance, forecast meteorological fields can be obtained from the US weather service (NCEP), the European weather service (ECMWF), NASA's assimilation research effort (GMAO), and others. Many research groups will be running models to forecast distributions of chemical trace gases, aerosols, and other substances in the atmosphere. To be able to ingest these data into the flight planner as well can be critically important. At least one model can forecast gravity-wave turbulence at high altitudes, which is highly desirable for the ER-2 and Global Hawk. After a flight the data-based equivalents of forecasts, analyzed fields, will be useful for post-mission analysis, as will climatological averages of these data fields for long-term advance mission planning.

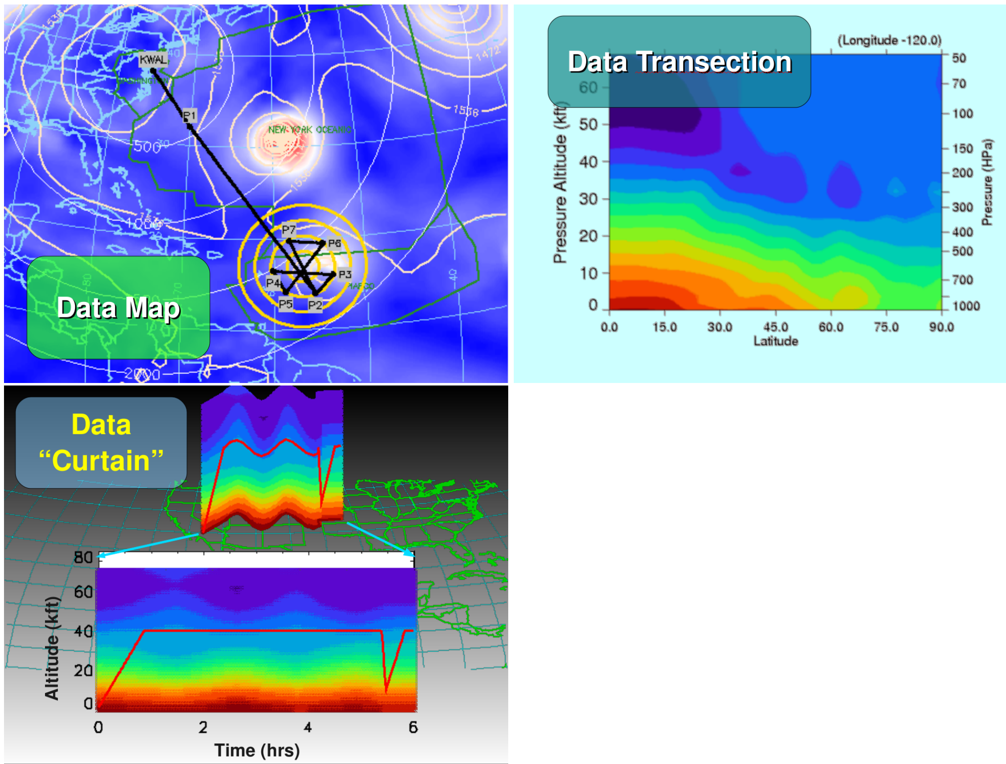


The forecast fields will be most useful when subsets of the data are extracted for close examination. These typically take three forms:

maps These are physical quantities on quasi-horizontal surfaces (most often, iso-surfaces of pressure, altitude, or potential temperature, as well as the tropopause). Note that the surfaces on which data should be viewed are not necessarily the same surfaces on which they arrive: planners need to be able to view Ertel's potential vorticity (EPV) on potential temperature surfaces, even though EPV comes in files on pressure surfaces. This calls for vertical interpolation.

transections As the maps are quasi-horizontal cuts through three-dimensional fields, transections are vertical cuts along a straight-line path between two points on the earth's surface. These are most often latitude-altitude extracts (i.e., a cut along a line of constant longitude).

curtains Like the transections, curtains are vertical cuts through the desired fields, but they follow an aircraft ground track rather than a straight line. These can be exceedingly useful for examining what meteorological phenomona the aircraft is likely to encounter.



In addition to meteorological fields, a good flight planner must be able to display markers and labels that indicate positions of interest. We call these "decorations", and they include:

location markers point out specific locations on the earth's surface. These may denote cities, or ground stations, or arbitrary navigational points.

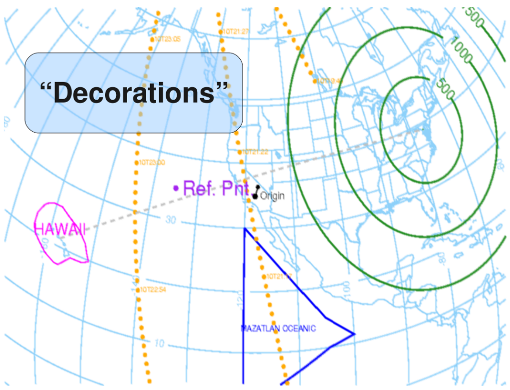
arbitrary polygons as the location markers denote points of interest, polygons mark areas of interes on the earth's surface. These may include restricted airspace, Flight Information Regions (FIRs), and mission operational areas.

range rings These consist of one or more circles centered about a user-determined point on the earth, marking out the distances (in user-selectable units) from that point.

satellite tracks Many flights take measurements coincidentally with satellites, so it is necessary to display the locations and times of the satellite instrument measurements.

great circle lines Occasionally it is useful to have a straight line between two points on a map as a reference line

altitude lines Occasionally, it is useful to have a line of constant altitude on a transection or curtain as a reference line



4.4 Handle a variety of plot types

A flight planner needs to be able to display data graphically in a number of different forms. The highest degree of flexibility needs to be granted to the scientists for choosing what to plot and how to plot it. It is not unusual to need two or three maps at the same time: one showing a false-color image of the potential vorticity field, one showing winds and geopotential heights, and another showing no meteorological data, but just some "decorations". You never know which quantities' plots are needed in what combinations. Therefore, the user must have the ability to choose how those plots are to be made: which are false-color images, and which are contours. And if contours, what kinds of line colors, styles, and thicknesses can be chosen to increase legibility when overplotted whith some other physical quantity? Even the order in which the plots and decorations are placed on the screen will vary, depending on what is more important in a given flight: sometimes temperature contours should be be plotted over wind vectors, which should be plotted over FIR boundaries. But sometimes the FIR boundaries need to be on top, and sometimes the wind vectors should be plotted over the temperatures.

There should be a set of reasonable default values for these plot settings, but scientists must also be permitted to re-make the plots with different settings of their own choice. Being limited to pre-made plots using fixed settings is not acceptable (and is indeed impossible when plotting data curtains which change from moment to moment during flight planning). If users are confused by too many choices and options, that indicates a poor user interface and poor default settings, not an overabundance of choices. We really do need the flexibility: here, more choices are good.

What follows is a brief description of some of the graphical displays that are possible:

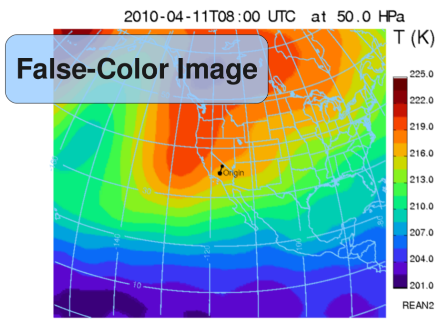
4.4.1 Map Plots

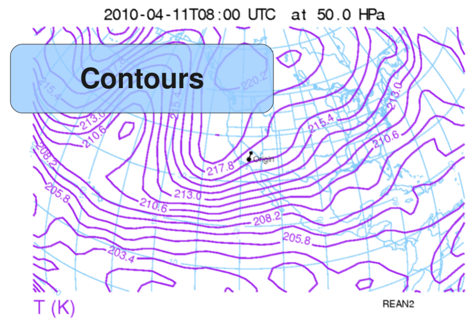
Map plots display the data maps described above, mapping a quasihorizontal surface to a 2D display area. It is important to be able to choose the map projection being used. For the flight track itself, the map projection seldom makes much difference, but the difference between a conformal projection and an equal-area projection can make a profound difference in how someone interprets the data plot.

Forecast model output can be plotted in any of several ways.

Scalar quantities can be plotted as:

false-color images Each value of the physical quantity is mapped to a color. Values between gridpoints may or may not be interpolated. This will give either a smooth appearance to the field (interpolated) or a blocky appearance (non-interpolated). Either may be required under different circumstances. A color scale is necessary for interpretation. The user must also be able to select a color scale/color table, as well as the data limits which map to that scale. One enhancement worth trying is to display several fields at the same time, using partial transparency.

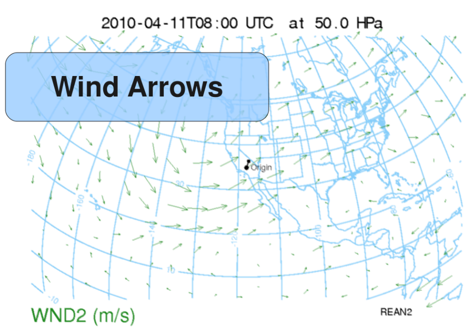


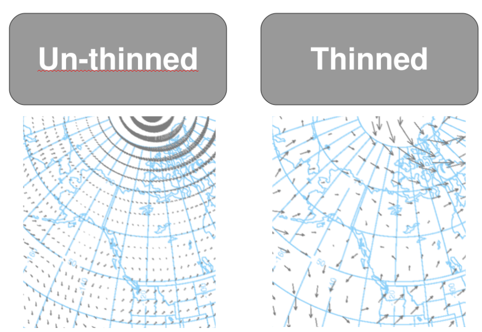


contours contours may take several forms. The simplest would consist of lines (of a user-selected color, style, and thickness) labelled with the quantity. A useful enhancement would be to replace the contour labels with colored contours (with a color scale by the side), or filled color contours (i.e., each contour is a closed color-filled polygon).

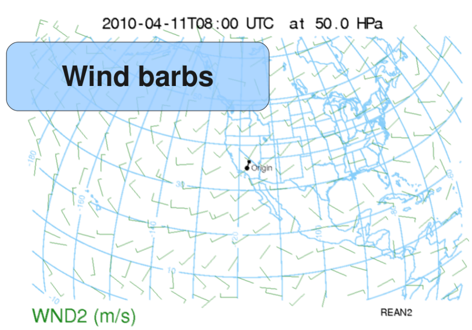
Vector quantities can be plotted in these ways:

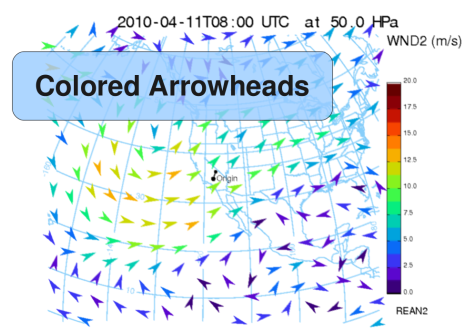
arrows In this form, the arrows are sized according to the magnitude of the vector quantity. The color, size, and thickness of the arrows must be user-selectable. Also, a thinning-out algorithm should be applied to prevent the display from being too crowded and unreadable when the data gridpoints are too close together. Care must also be taken on map plots, to ensure that the vector directions are transformed properly into the map projection.





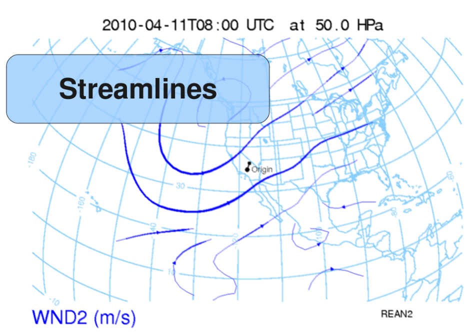
barbs In this form, vectors (typically horizontal wind) are displayed as line segments of uniform width, with marks at their tail ends to encode the magnitude values. Instead of pointing the “toward” direction, barbs point in the "from" direction of the vector. Like the arrow, barbs are displayed with user-selectable colors, thicknesses, and sizes. And they, too, must have a thinning algorithm applied.





colored arrowheads In this form, the vector direction is represented by the direction of a uniformly-sized arrowhead, and its magnitude is coded by the color of the arrowhead, as in a false-color image. Again, the size of the arrowheads must be selectable, and the thinning algorithm must be available. The color scale and the data limits must also be user-selectable.

streamlines In this form, arrows are replaced with lines of steady flow. The thickness of the lines indicates the magnitude of the vector field, and the orientation of the lines (helped by the occasional arrowhead) indicarted the direction. The line color must be user-selectable.



Additionally, the source of each data field should be noted somewhere in the margins of the display, especially in the hard copy.

4.4.2 transection plot

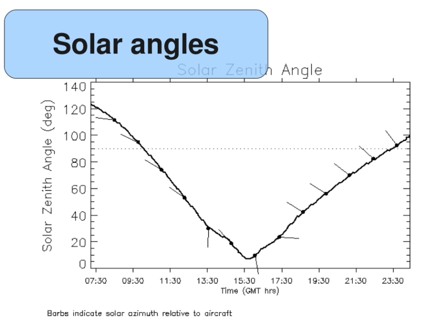
This will display the data transections described above. Scalar and vector quantities are to be plotted as for the map plots described above.

4.4.3 curtain plot

This will display the data curtains desribed above. Scalar and vector quantities are to be plotted as for the map plots described above.

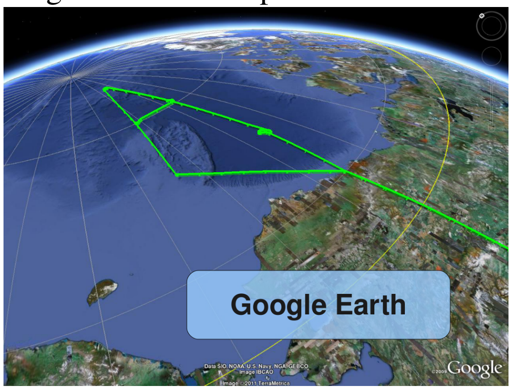
4.4.4 Solar/Lunar zenith/azimuth angles

It is frequently important to know when the aircraft will be in light and when in darkness. And with some payloads, it is vital to know the sun's horizontal location relative to the aircraft. Displaying the zenith angle as a function of flight time gives us the former, and attaching barbs along the zenith angle curve gives us the latter. Note that to be truly useful, the azimuth angle must be corrected using forecast winds, since crosswinds do affect the angle at which the aircraft points.



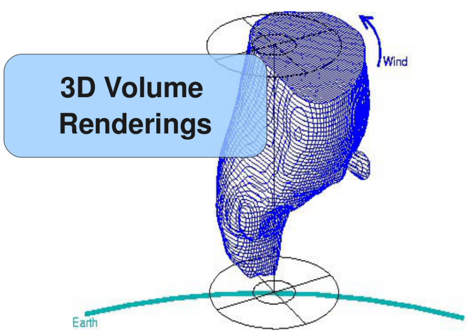
4.4.5 Google Earth

It is useful to be able to display flight tracks, "decorations", and meteorological fields in a tool like Google Earth. Certain technical difficulties exist with trying to manipulate a three-dimensional flight path in Google Earth, that prevent its use as a serious flight planning tool. And foregoing traditional map projections in favor of a perspective view of the spherical earth can be less than optimal for quantitative interpretation of the meteorological fields. Nevertheless, Google Earth (or a similar tool) can be useful for quickly conveying an overview of a flight. It also makes good visuals for public affairs materials.



4.4.6 3D volume renderings

This is a way of displaying three-dimensional meteorological fields. This kind of plot shows iso-surfaces of a field quantity that encompass volumes within three-dimensional space. Typically, the volume is rendered as a blob of colored translucent material floating in space. Although these plots can be visually impressive and thus useful for public affairs materials, it is difficult to obtain quantitative information from them. Their scientific useful is limited. As pretty pictures of limited utility, they are sometimes referred to as "Jell-O shots".

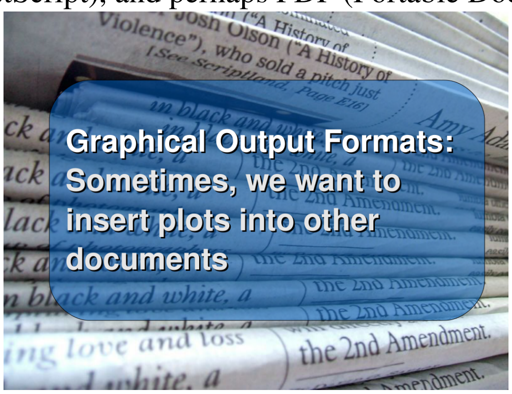


Where do the data to be plotted come from? They may be read from local files, or obtained over the Internet. If the flight planner reads from local files, there are a number of formats that it should be able to read: GRIB/BUFR, NetCDF, and the various flavors of HDF (HDF4, HDF5, and EOSHDF/EOSHDF5). An alternative is to use a network data protocol such as OPeNDAP to obtain the data, but there are few good OPeNDAP servers currently available. At any rate, different data sources have their individual strengths and weaknesses, so users should be able to choose from multiple sources such as NCEP or GMAO.

4.5 Handle a variety of output graphical formats

A science flight planner needs to be able to display these plots on a user's video monitor and permit interaction with the flight track. But for preparing briefing materials, it is also necessary to generate hard copy, in the form of graphical files that can be incorporated into documents. These should be better than mere screen captures with limited resolution; they ought to look nice in slide presentations and reports.

The user must be able to select the output format; the most useful formats are PNG (Portable Network Graphics) image files, PostScript (including encapsulated PostScript), and perhaps PDF (Portable Document Format).



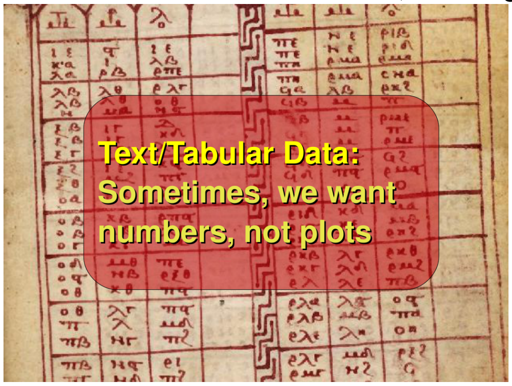
4.6 Handle a variety of text displays

Not all information displayed by the flight planner should be graphical. There is also a need for textual and numeric data.

A summary of basic flight information is useful: aircraft identification, proposed takeoff date and time, flight duration, and total estimated fuel used. The use should also be able to enter short descriptive notes of arbitrary text to be attached ot the flight plan and printed out where desired.

A table of defined reference locations can be helpful, consisting of a label, the latitude and longitude (in user-selectable units of decimal degrees,

degrees/decimal-minutes, and degrees/minutes/seconds), and perhaps a short descriptive note. These locations would include not only certain way points, but other locations used for reference (such as ground station locations).



The most important text output is a table listing values along the flight track. The quantities to be displayed must be user-selectable, and the list should include:

- date
- UTC time
- local (launch site) time
- elapsed flight time (in decimal hours or HH:MM format)
- latitude (in dd.ddd, dd-mm.mmm, or dd mm ss.sss format)
- longitude (in dd.ddd, dd-mm.mmm, or dd mm ss.sss format)
- altitude (in km, ft, and kft)
- pressure
- course
- magnetic course
- magnetic correction
- cumulative distance traveled)(in km or nmi)
- solar zenith angle

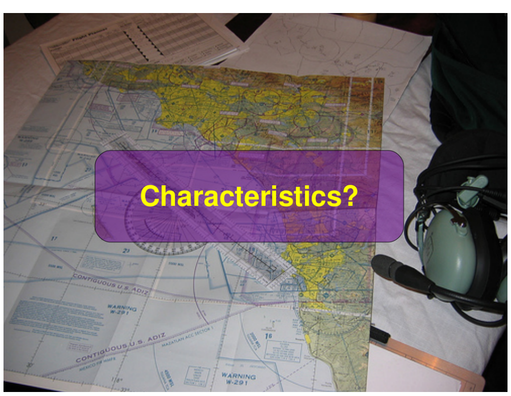
- solar azimuth angle (wrt aircraft)
- temperature (in Kelvin, degrees Celsius, or degrees Fahrenheit)
- wind speed and direction (speed in m/s or kts)
- heading correction for winds
- true heading
- time correction for winds (in decimal hours of HH:MM format)
- wind correction to solar zenith angle
- time to next way point
- distance ot next way point
- fuel remaining
- fuel burned so far
- name of defined location (if withina threshold distance)

Data along the flight path would be spaced every N minutes apart, where N is user-selectable. (Five minutes is a good default.)

It would also be helpful to be able to restrict the listing to selected section of the flight, instead of the entire flight. This can be done by time, or by way points.

Like the graphical displays, these text displays should be output in any of several formats: plain text, word processor (e.g., rtf), or spreadsheet (e.g., csv).

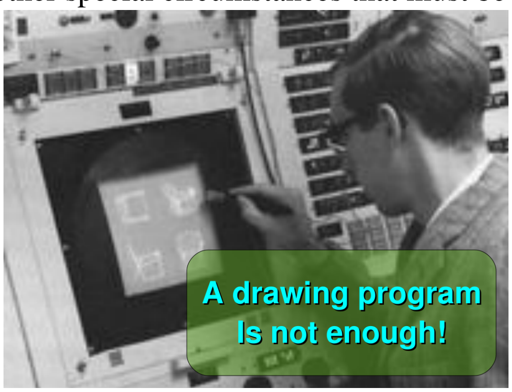
4.7 Desired Characteristics



4.7.1 Don't be just a drawing program

It is highly desirable to be able to plan a flight by connecting and moving way points on a map. This is a crucial element of the user interface of a good flight planner. But this is not sufficient.

The scientists must be able to design vertical maneuvers into the flight plan. But we found in an early version of the GSFC flight planner that drawing lines on a curtain plots also is stil not enough. With some aircraft, each portion of a flight (each line segment in a drawing-style user interface) may have its own air speed or other special circumstances that must be entered.



A complicated series of maneuvers can be hard to set up as a series of line segments in a drawing program. Designing certain kinds of flights (such as crenelation flights) took a long time and was difficult to change. What is needed is to be able to collect a sequence of elementary maneuvers into a maneuver that takes a few parameters. For example, the sequence

1. cruise climb for _ nmi
2. descend to _ feet
3. fly straight-and-level for _ minutes
4. ascend to maximum altitude

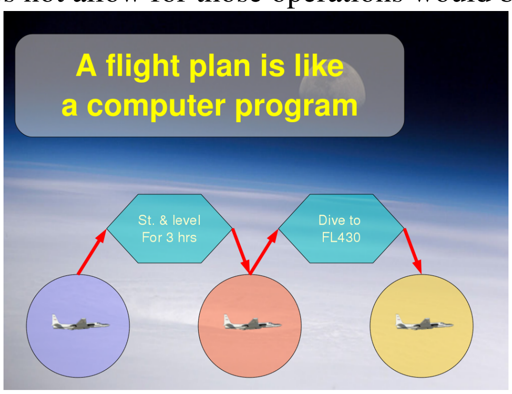
could be collected into a single

1. cruise-climb-with-VPM-at-end

This becomes a little easier if a flight plan is treated as a sequence of maneuvers, each of which operates on the aircraft's current state to produce a new state. By "state", we would include the aircraft's longitude, latitude, altitude, time, true air speed, true heading, and fuel load. A segment of straight-and-level flight, for example, would change the longitude, latitude, time, and fuel while leaving the other elements of the state unchanged.

If we think in these terms, a flight plan becomes very much like a kind of computer program, with the maneuvers being roughly equivalent to programming statements. The flight planner then becomes a sort of integrated development environment (IDE). This in turn opens up useful ideas in detecting and handling user errors in a flight plan (e.g., making the aircraft fly after it has run out of fuel, or flying it under the earth's surface).

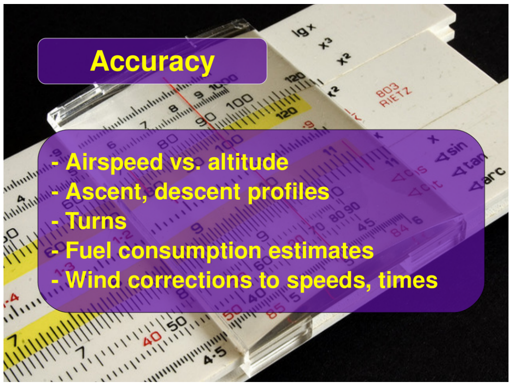
A good user interface, whatever graphical elements it may have, will permit the user to insert, delete, and change the parameters of a maneuver. Performing these actions graphically is very nice, but a user-friendly graphical interface that does not allow for those operations would be detrimental.



4.7.2 Simulate aircraft performance as accurately as possible

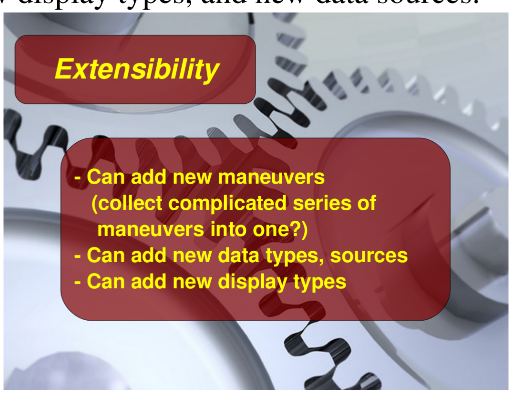
The more accurately the aircraft's behavior is simluated, the better the timings will be. Air speed as a function of altitude, ascent and descent profiles, and turning characteristics all need to be determined empirically. Where possible, fuel consumption should be estimated, too. And with a given aircraft, any or all of these may change with payload configuration.

The same meteorological data that are available for plotting in displays, are also available for interpolating along the flight track. Wind values along the three-dimensional flight path can be used to correct the timings and the heading.



4.7.3 Be extensible

Even after two decades, we still encounter new needs in flight planning. A good flight planning tool will permit the addition of new aircraft types, new maneuvers, new display types, and new data sources.



4.7.4 Miscellaneous features

Find and display satellite coincidences We have found that simply displaying satellite overpass locations and times is often not enough. A change in take-off time can shift the coincidence point in ways that some people perceive as counterintuitive. The flight planner should have a function that computes the closest coincidence in space and time and puts a big colored dot at that point, labelled with the time.

Display and edit multiple aircraft flights simultaneously Because some missions have multiple aircraft in the sky at the same time, it is useful for a flight planner to be able to plan several flights simultaneously. The best way seems to be to have separate editing controls for the different flights, with display that show all the flights.

Allow for versioning of flight plans One of the side effects of being able to work through a variety of flight scenarios is a plethora of flight plans. A good flight planner should be helpful in managing the various iterations of a flight plan, both alternatives and versions of those alternatives.

Allow for separate saving and loading of flight plans and display configurations Having lots of user choice and customization is good, but not if the user has to set up all their preferences from scratch every time they start planning a new flight. They should be able to save and restore their settings. And ideally, some settings should be saved as preferences (i.e., they override the defaults for that user), and some should be saved in a way that associates them with a specific flight plan.

Display data as time animations as well as static plots Especially for long-duration aircraft, the large-scale meteorological context can change appreciably between takeoff and landing. Static plots are good for some purposes, but scientists also need to be able to look at animated versions on their screen displays. Ideally, they should be able to set up a plot in a static version, getting the line styles and color scales just the way they want them, and then switch to "animated mode". If it highly desirable that the animation should not simply loop around and around, but it should have a control that the user can grab to pull the animation back and forth in time over a small segment of the flight. It might also be a good idea to synchronize the various animated displays, so that setting the time on one display causes all the displays to move to that same time. The user should also be able to make a hardcopy of any desired frame of the animation.

Allow for different kinds of horizontal paths At some times and some places, the aircraft will follow a great-circle route. But in other circumstances, flight ops may prefer a rhumb line (line of constant heading) for ease of navigation. Over short paths, the two are nearly the same. But over longer distances, they differ significntly. Good flight planning software needs to be able to use either kind of path.

Compute magnetic corrections for headings Atmospheric scientists do their work in terms of true headings. Pilots frequently prefer magentic headings. The flight planner should be able to estimate the magentic corrections.

Allow for reading longitude, latitudes, times, and/or altitudes off a graphical display The user needs a way of reading cursor positions off a screen display, in that display's units. On map displays, this means that the cursor position is given as longitude and latitude. On curtain and transection display, the position would be given as longitude/latitude/time and altitude.

Chapter 5

The Path Ahead

For planning science flights, we need the functions and capabilities described above. We have almost all of them in the Goddard Flight Planner. But the Goddard Flight Planner has some drawbacks:

- It is a purely local program that requires installation
- Written in IDL, it requires the user purchase an IDL software license
- Most of its data access is for local files written in the Goddard-developed “df” format.
- The user interface is somewhat clunky. In particular, editing flight plans should be more intuitive.

To remedy these shortcomings, we want

- some form of web-based application. It can run entirely on a server, displaying on the local browser; or it can split tasks between the server and something like a java applet. But it should not require local administrative priviledges to run.

- an application that will run on the widest possible variety of Windows, Macintosh, and Linux machines, without the need to purchase extra software or reconfigure the operating system

- data acquired and processed on a central server (possibly in the field), to be rendered into a plot on either the server or on the client end.

- a cleaner, more intuitive user interface

Appendix A

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